Outline

- What is wrong with the LHC inter-magnet connections, quench protection and energy extraction?
- What is a “safe” energy to run at without repairs?
- The present concept for repairs and modifications

- Chamonix 2010

All slides: *http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=67839*

Summary: *http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=83135*

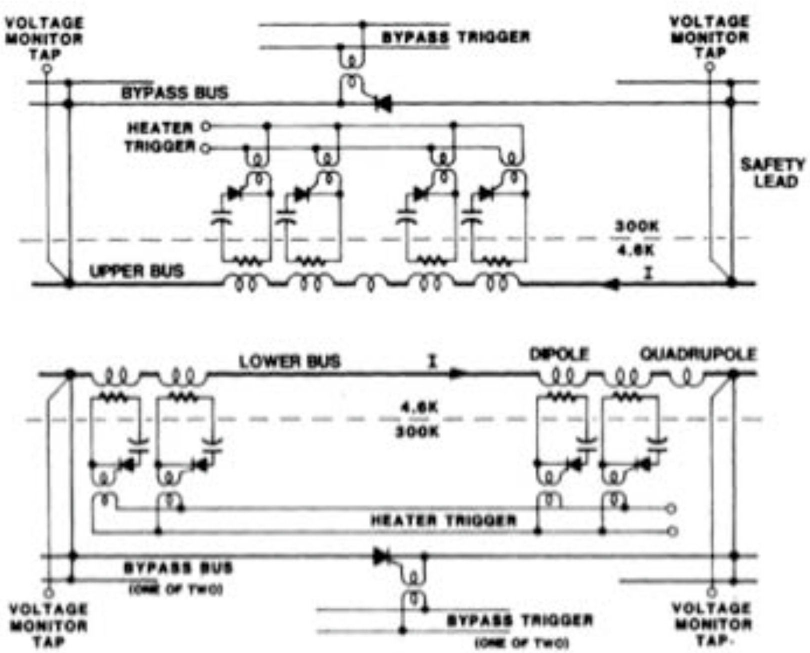
  - Some major decisions on direction & schedule
  - Possible consequence
- Personal Perspectives

Studying the LHC splices

- **A "task force" (all the members are from CERN) was formed**
  - Chairman: Francesco Bertinelli
  - Initial charge: Develop a 5 TeV solution by June for a 6-month shutdown starting in December 2010
  - Develop a 7 TeV* solution for a later, longer shutdown
- **Lots of Fermilab expertise and effort**
  - At CERN: Bob Flora, Howie Pfeffer, Jim Strait, Sandor Feher
  - Others at Fermilab but in contact
  - From BNL: George Ganetis

* In this seminar, I am always referring to energy per beam. 7 TeV = 14 TeV CM

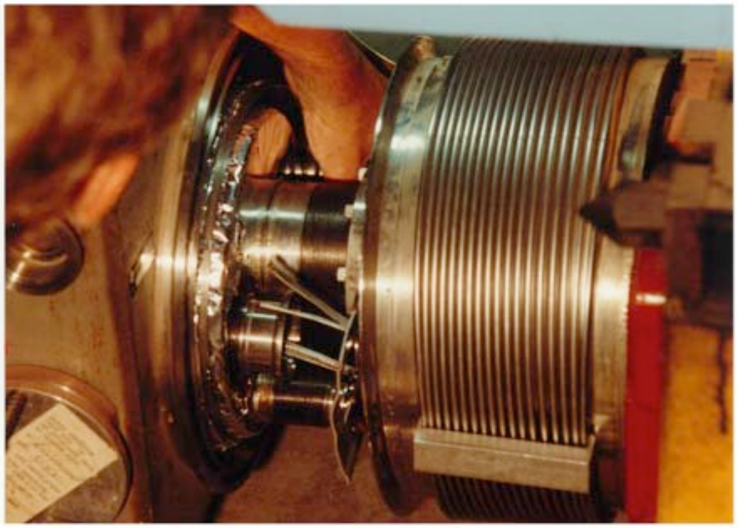
Tevatron QPS Unit

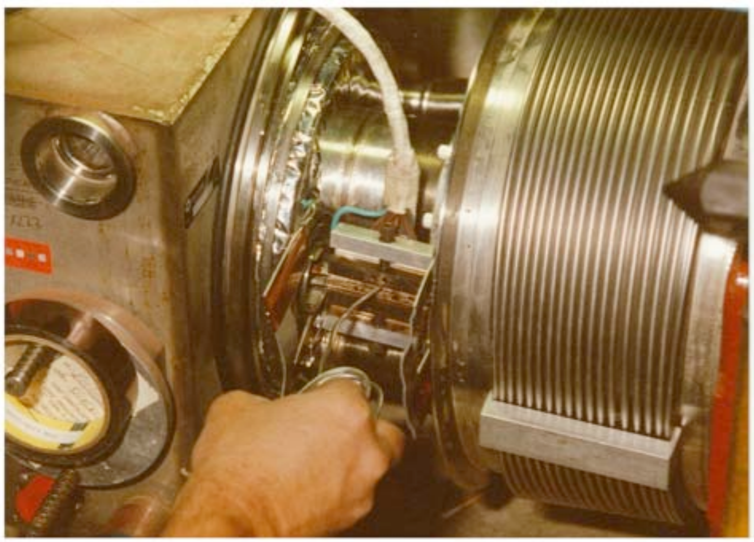


Tevatron QPS

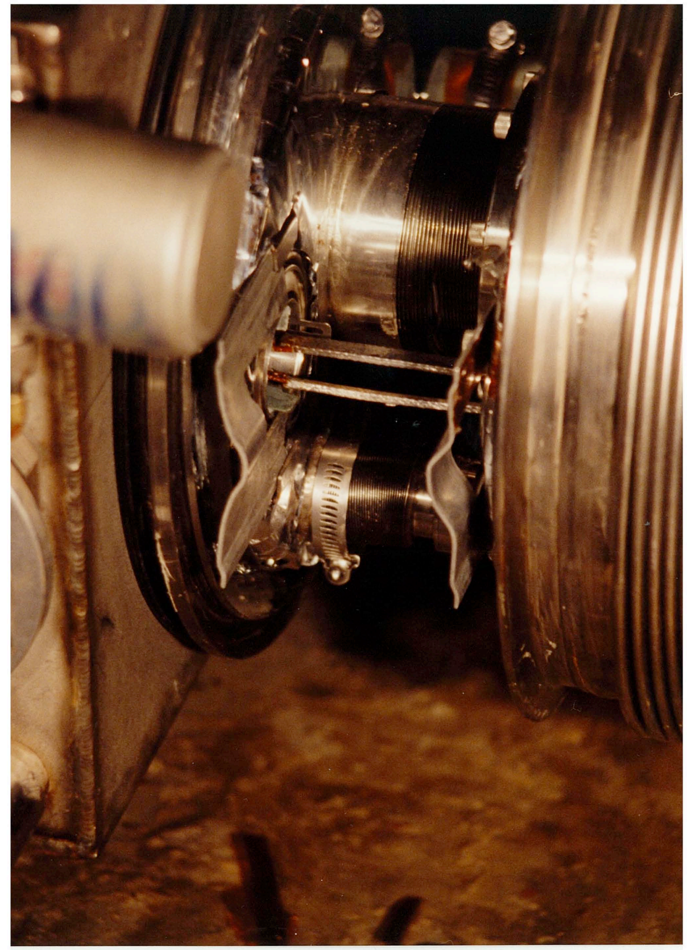
- **Tevatron was a fixed-target machine. One ramp/minute**
  - Cold diodes not appropriate for bypass
    - Triggered SCRs at room temperature were used
  - Bypass bus is independent of return bus
    - Decay time constant set by MIITS (= peak temperature) in safety lead
  - Redundancy - duplicate independent bypass circuit and trigger
    - Automatically & frequently tested
  - **Every mm of cable & bus is protected!**
    - Detection, heater protection & **bypass** is applied to all quenching magnets, splices and buses. **No exceptions!**

Tevatron Splice Procedure

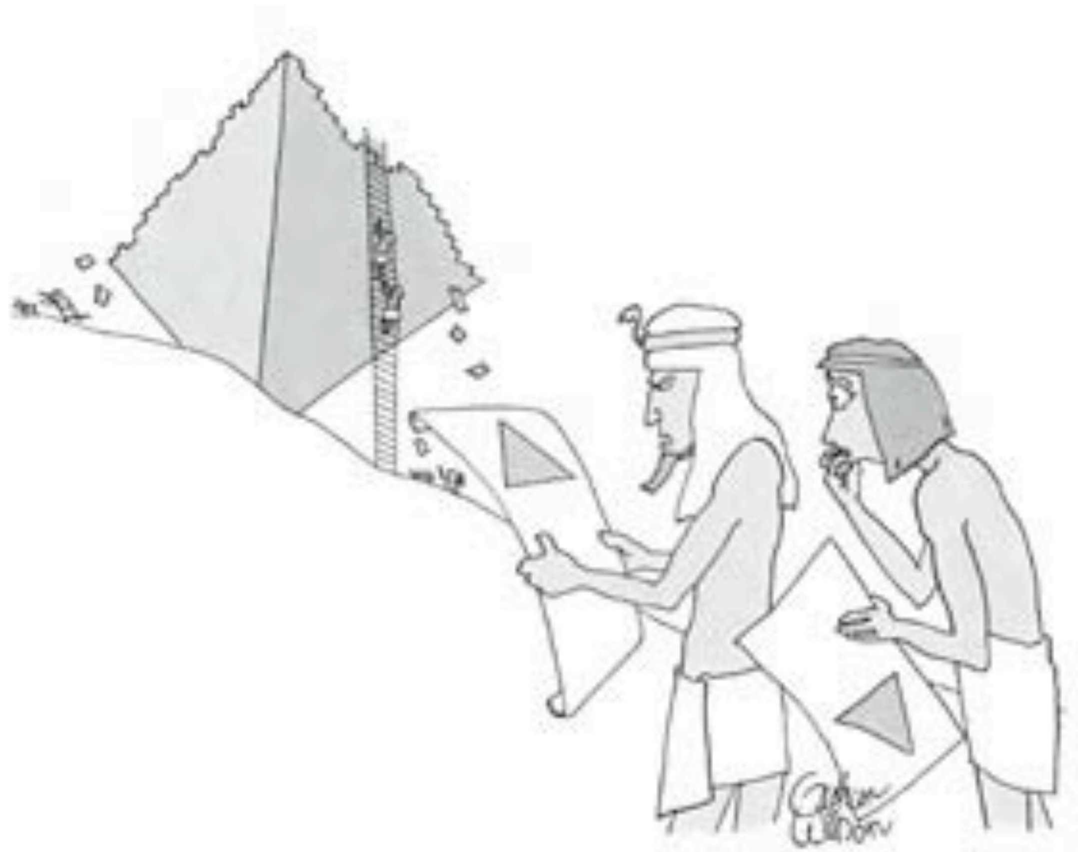




EASY TO INSPECT



Observations

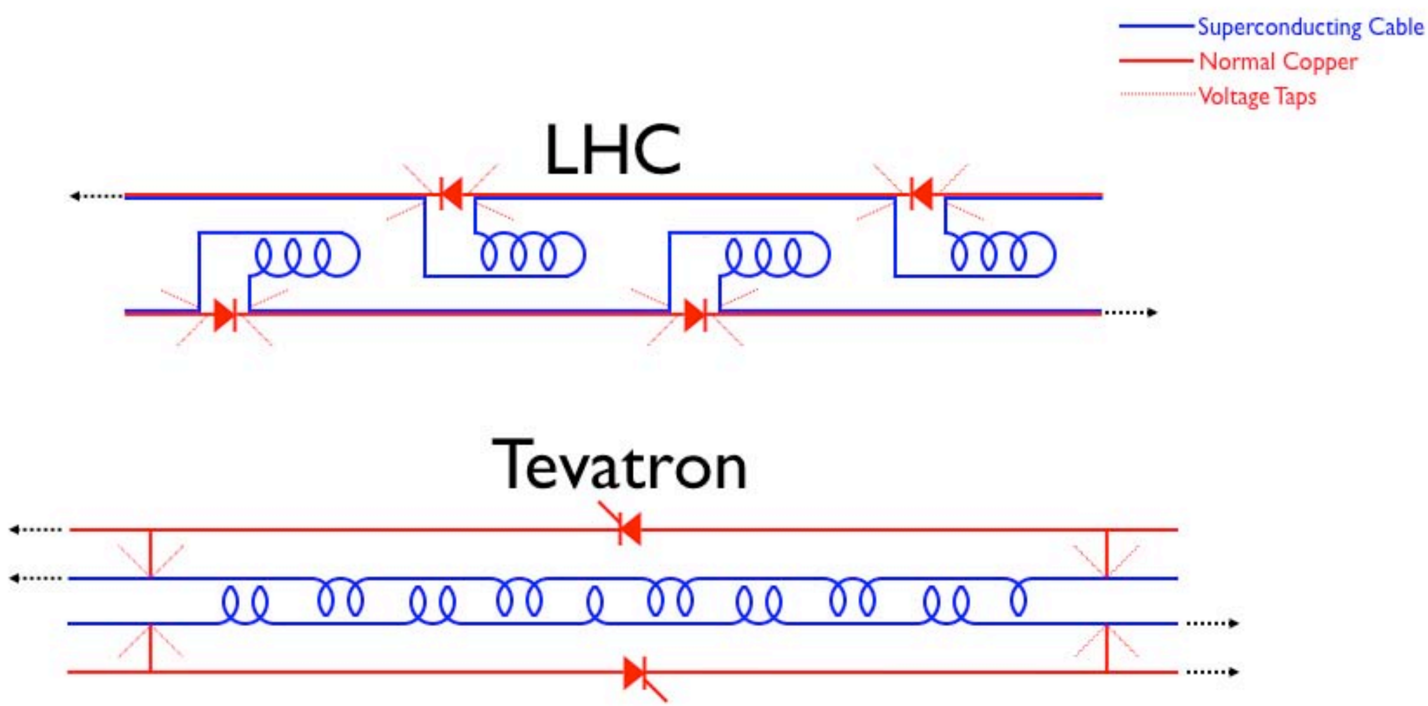


"I think I've spotted your problem."

Bypass Scheme Comparison

❖ **The LHC has bus work that is not properly bypassed**

- Its time constant is very long (~100 s)
- Initially, the bus detection threshold was very high (>1 V)

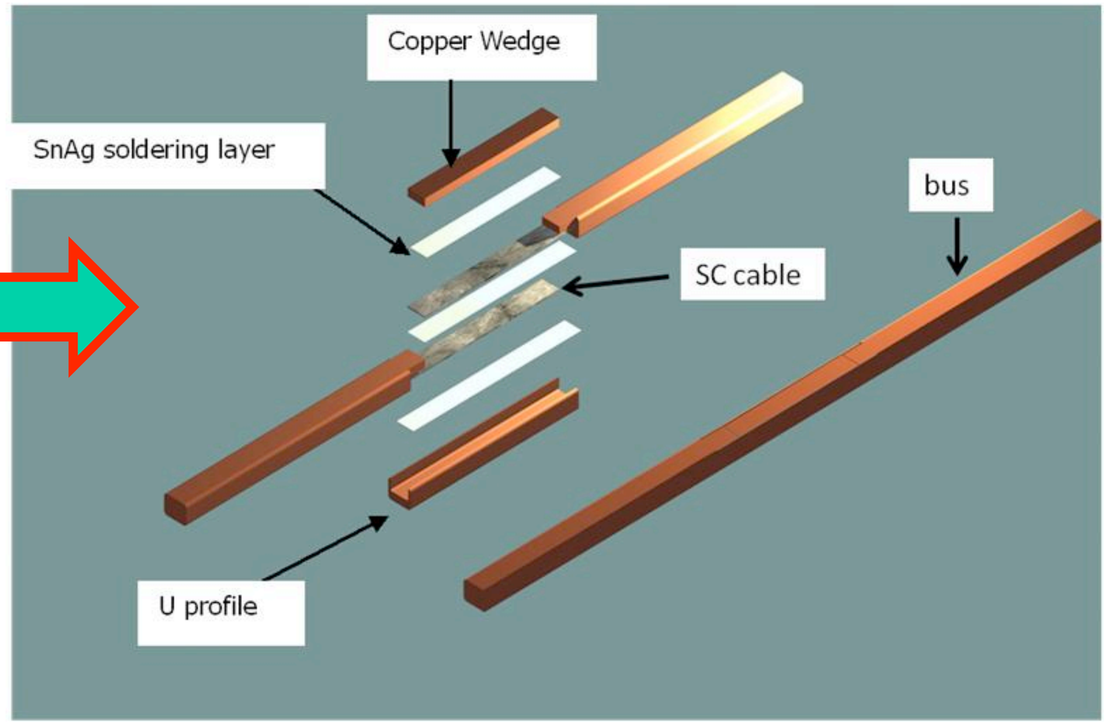


LHC Inter-magnet Joint

The main circuits of the LHC (RB, RQD, RQF) have about 24000 splices.

Out of these there are:
- 10170 interconnect splices and
- 13796 magnet splices

Interconnect splices are not protected by diodes and in the case of a problem all the current of the circuit passes through them with a decay time of ~100 s

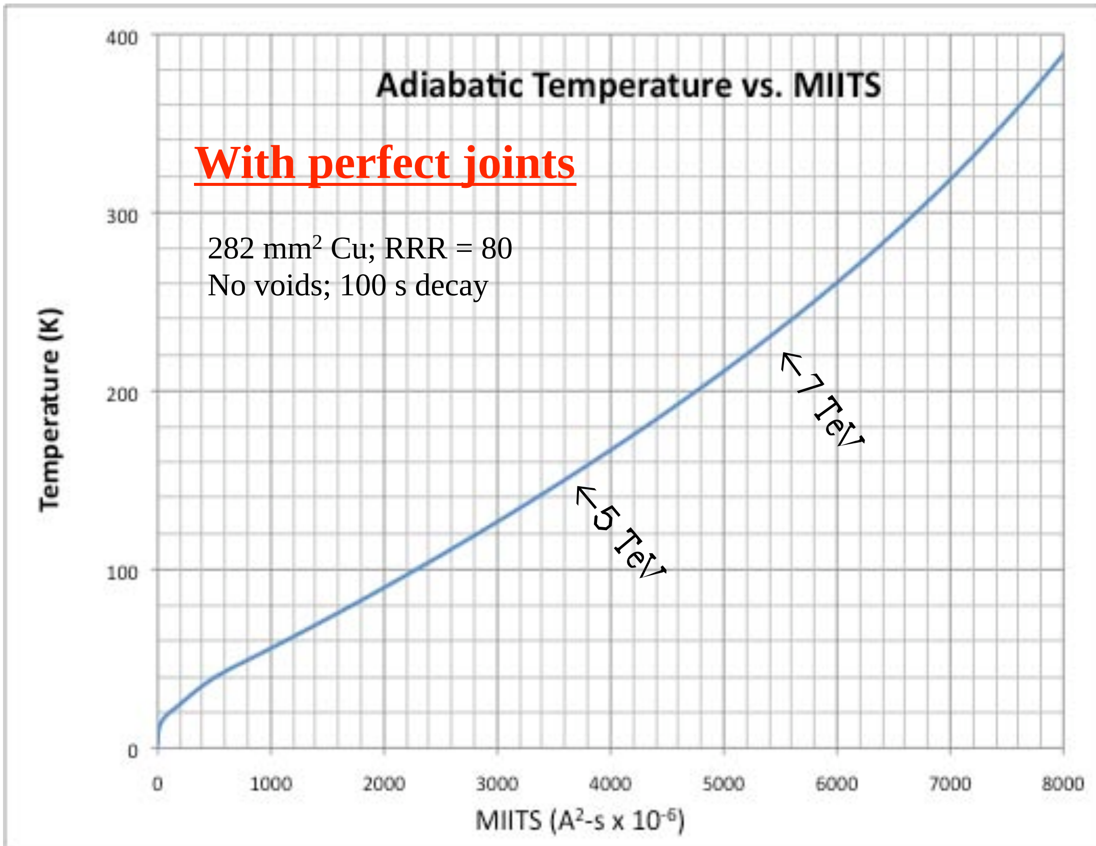


Nominal interconnect splice resistance:
- At cold: **300pΩ**
- At warm (300K): **10μΩ**

For the LHC to operate safely at a certain energy, there is a limit to how big a splice resistance can be

P. Limon

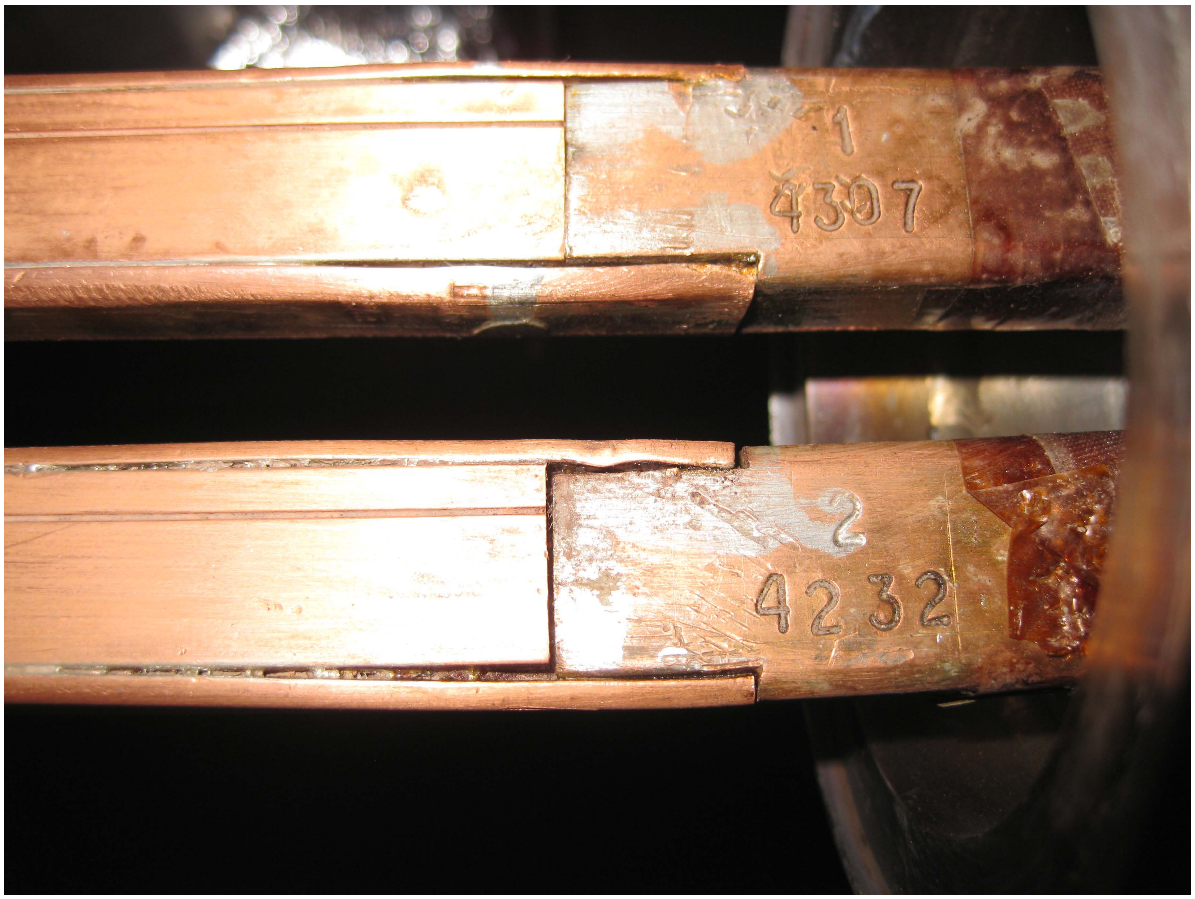
LHC Temperature vs. MIITS



So, what happened on 9/19?

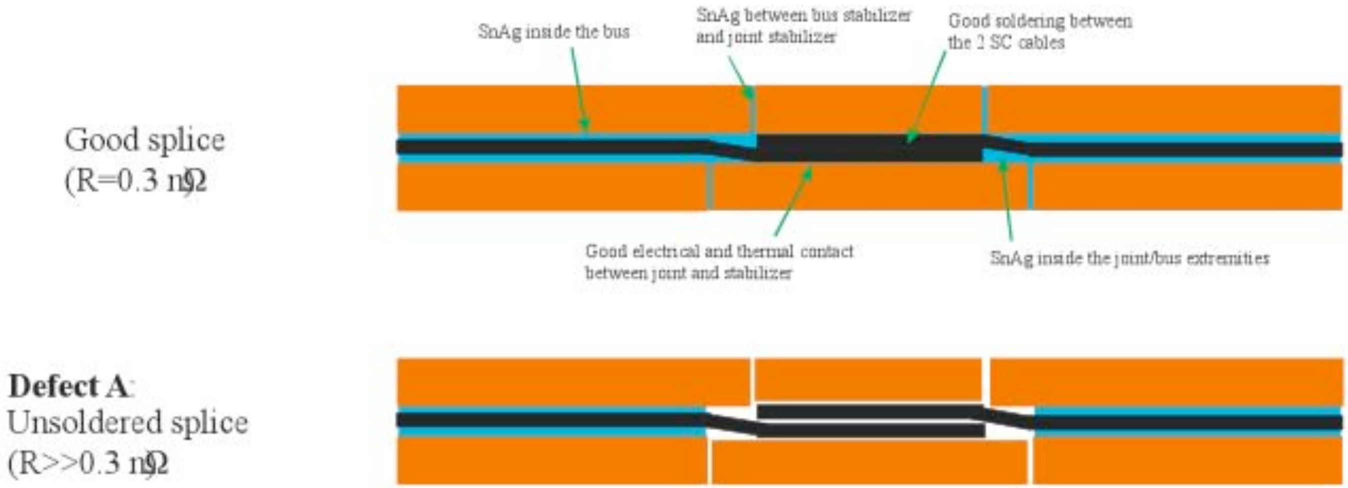
Bad, Bad, Bad

❖ **Not all the joints are perfect!**



LHC Temperature vs. MIITS

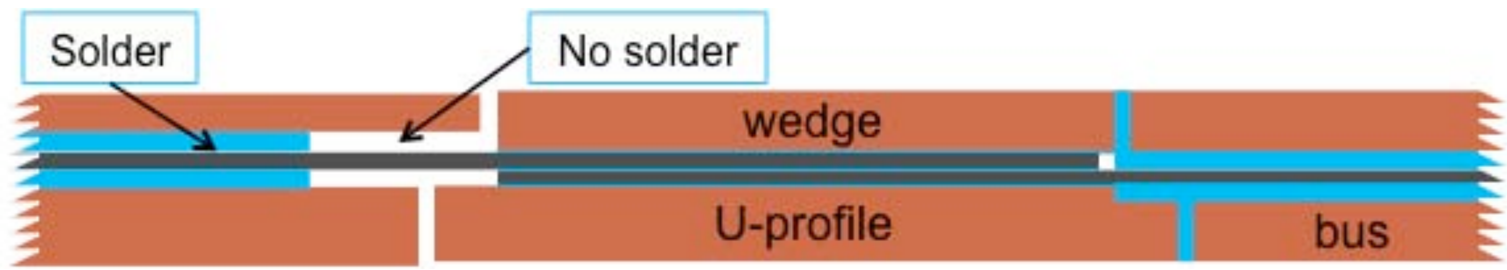
❖ So, what happened on 9/19?



- o Poor splice; post analysis finds 200 nΩ during ramp
- o Bad thermal contact; little quench propagation outside of ~150 mm
  - ▪ 1 V threshold @ 8700 A; T>1500 K
- o Is this safe with new QPS?
  - ▪ 300 μV threshold @12,000 A; T< 200 K
- o **New QPS protects against this**.

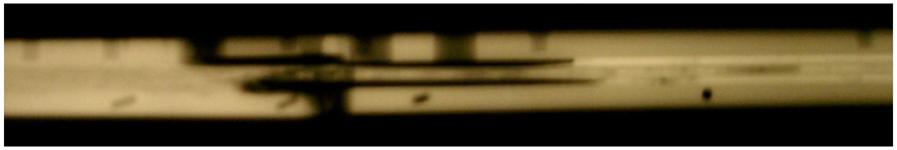
LHC Temperature vs. MIITS

- **But wait; there's more!**
- **The Verweij / Pfeffer conjecture**
  - Not actually a conjecture, because it's a fact
  - Voids & poor electrical contact that forced current through SC

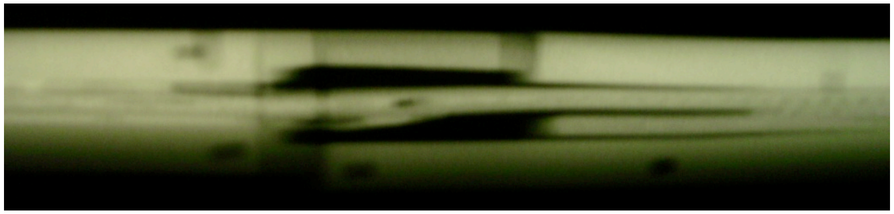


  - The final temperature depends on the length of the void
    - Cable blows up during dump, even at 300 μV detection if void is >x cm long
  - **What is the safe energy to run at?**
    - It depends on the length of voids, which are characterized by their 300 K resistance

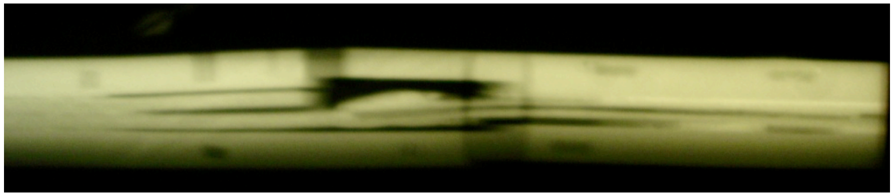
Sample Joint X-Rays



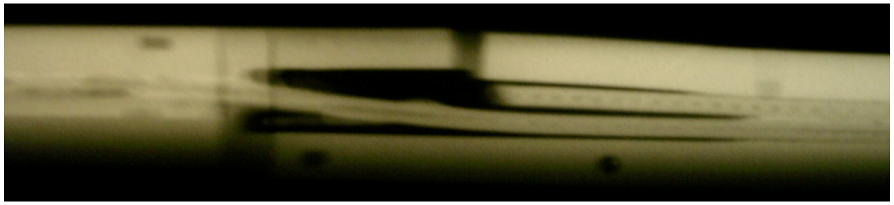
Sample 1 (61 μΩ)



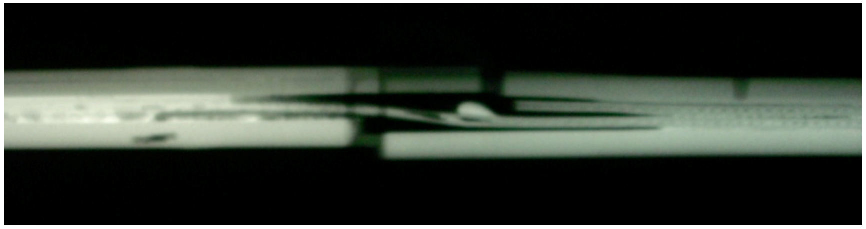
Sample 2A left (32 μΩ)



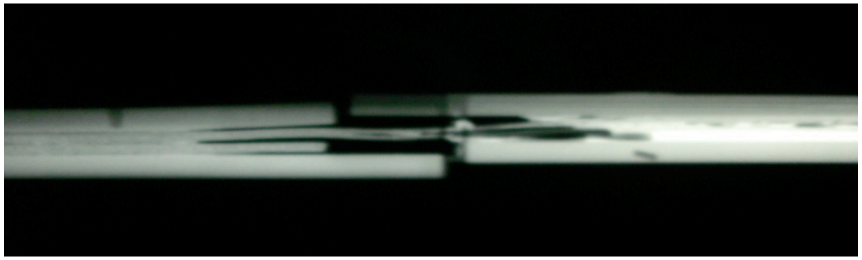
Sample 2A right (43 μΩ)



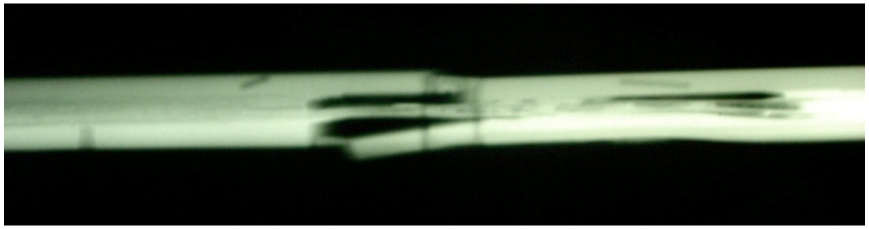
Sample 2B (42 μΩ)



Sample 3A left (26 μΩ)



Sample 3A right (43 μΩ)



Sample 3B (21 μΩ)

Pictures by J.-M. Dalin

What was done wrong?

- **Conceptual mistakes**
  - Superconductor and bus not protected everywhere
  - Assumed all installation work would be perfect
  - Assumed bypass bus could not spontaneously quench
  - Poor estimate of the maximum credible accident
- **Design errors**
  - Joints not overlapped enough (contact area)
  - Joints not clamped
  - Joints not easily inspected
  - Wrong installation solder; same melting temperature as bus solder
  - Not enough voltage taps
- **Execution errors**
  - Installation done by piecework, jeopardizing quality
  - Poor quality assurance plan and quality control
  - Poor equipment maintenance; some equipment malfunctions

Possible Solutions

1. **Somehow reduce the current decay time constant**
    - Install a cold or warm bypass so the bus is protected in series with the magnets. Then $\tau \leq 1$ s
        - *Install safety leads in some short straights. Probably not feasible*
        - *Or, bypass & quench the whole sector. Potentially dangerous.*
    - Break up the circuit so the decay time constant is shorter
        - *May not be good enough for any reasonable time constant*
2. **Limit the beam energy to a "safe" level**

    This is acceptable for some period of time, but not forever
3. **Make every splice "perfect," or, at least, good enough**

❖ **It seems to me that only option 3 is viable**
- With a bit of option 2

Question: Can we find every bad joint or will we have to repair them all?

Finding Bad Joints

- **Superconducting splices**
  - This is taken care of with nQPS and 300 μV threshold
- **Finding bad bus joints; Not so easy**
  - Voltage taps only at quads
    - Segment = Two or three joints in dipole bus; eight (or more) in quad bus
  - Cannot be done if cable is superconducting
    - Must warm to > 20 K;
      - *RRR not well known; Temperature not well regulated*
  - Measuring across segment not very accurate at the tens of μΩ level
- **Most accurate way is to open suspect joints and measure resistance at 300 K. The "R-16" measurement. Very time consuming.**
- **There are some other methods being tried**
  - Pfeffer thermal amplifier; a possible way to find bad segments
    - A method to put current through bus without damaging superconductor
  - Determining RRR more accurately

Resistances at warm II: the Biddle

A heroic effort (led by B. Flora) was undertaken to measure bus bar segment resistances at warm. Measurements were taken **by hand** (100,000 numbers!) in the tunnel in all sectors.

The measurements had a 1% accuracy and, predictably, worked o.k. for the RB at 300K (when looking for a 2.5% defect), but worked less well for the RQ and at 80K were not sufficiently precise to spot outliers. When a bad segment was found, all joints in that segment had to be opened for further measurements and repair.

P. Limon

Biddle Measurements Recap

- The most reliable Biddle measurements (RB at room temperature only) are shown in the table below
- Five sectors were measured at warm and the worst splices were opened up and repaired
- The table below shows the situation **after** the repairs

Circuit/ Sector	Temperature spread (K)	Excess resistance spread	Highest remaining excess resistance	Excess resistance limit 90%CL
A12 RB	1.1	13	37	51
A34 RB	1.9	10	35	47
A45 RB	0.9	17	53	78
A56 RB	0.4	9	20	34
A67 RB	0.6	14	31	48

P. Limon

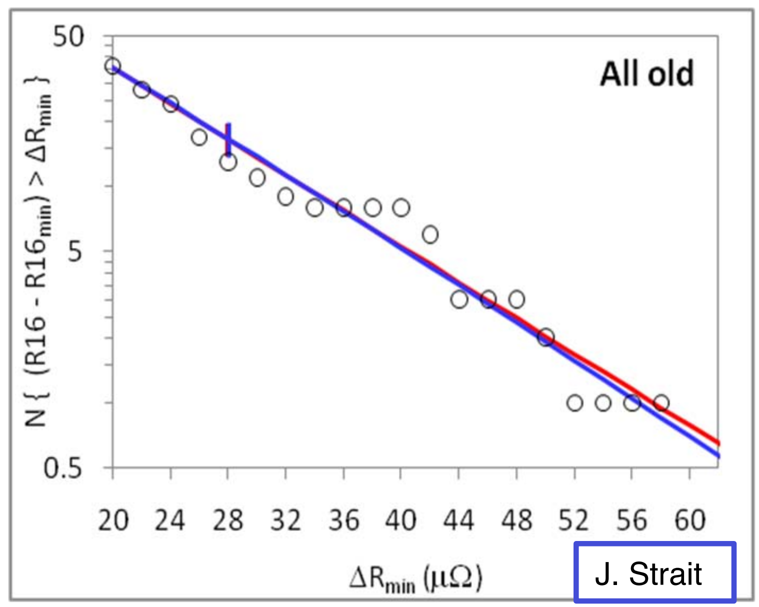
Repairing LHC Joints
& Chamonix 2010

The Worst Remaining Splice

- **The only reliable Biddle measurements are the RB measurements at 300K (5 sectors)**
  - o Worst **measured** excess resistance RB: 74±15µΩ(A45)
  - o Worst **remaining** excess resistance RB: 53±15µΩ (A45)
- **The worst measured R16 measurement is 60±1 µΩ**
- **To find out the worst remaining splice in the machine we need to rely on a statistical extrapolation.**

•The statistic of the 'worse splice seen' is not particularly robust
•We have performed a statistical analysis on the R16 measurements
•This gave a confidence bound at the 90%CL of R_{excess} = 98µΩ

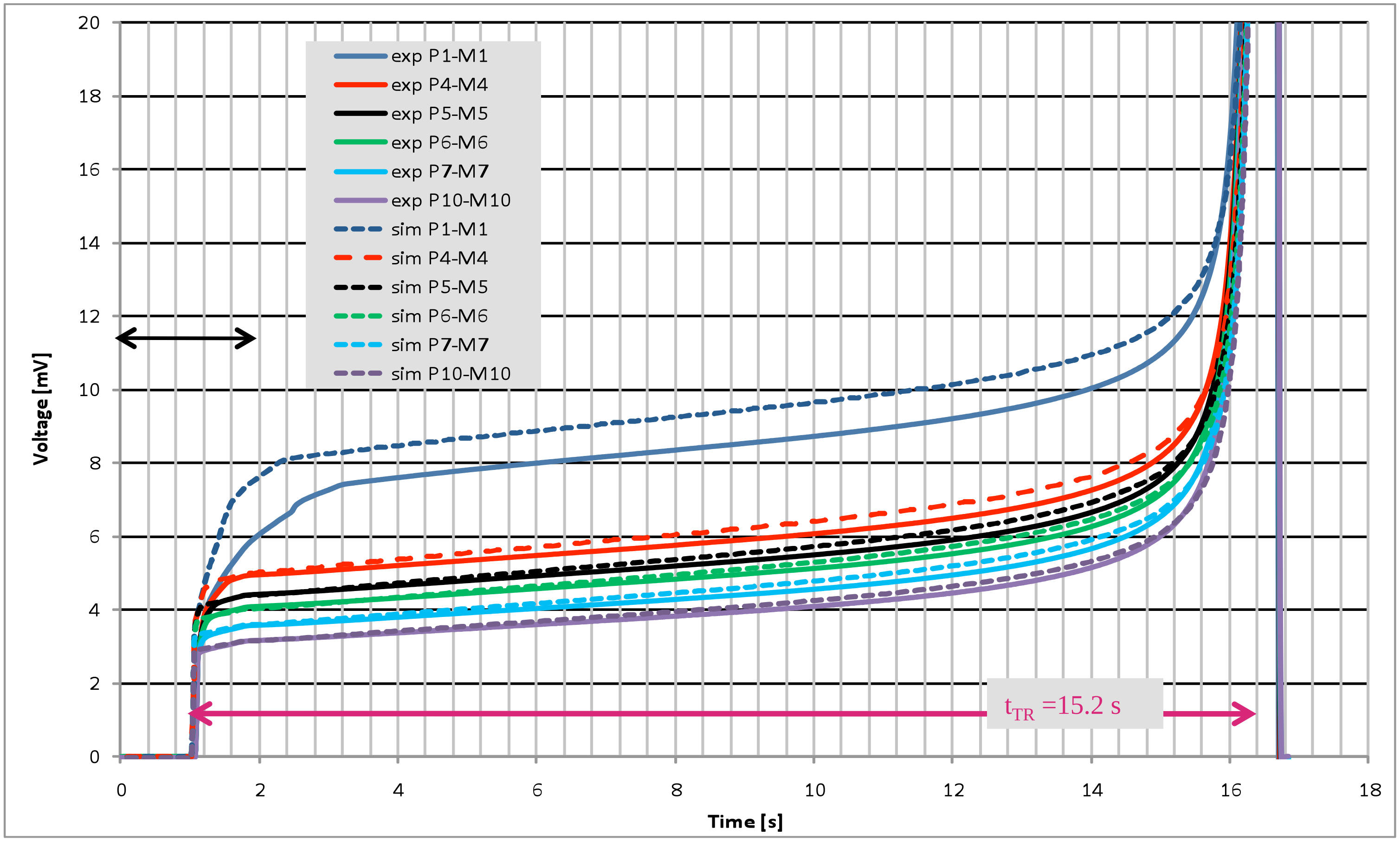
Most realistic max. excess resistance (RB, RQ)
R_{max} ≈ 90 µΩ (LMC 5/8/2009)



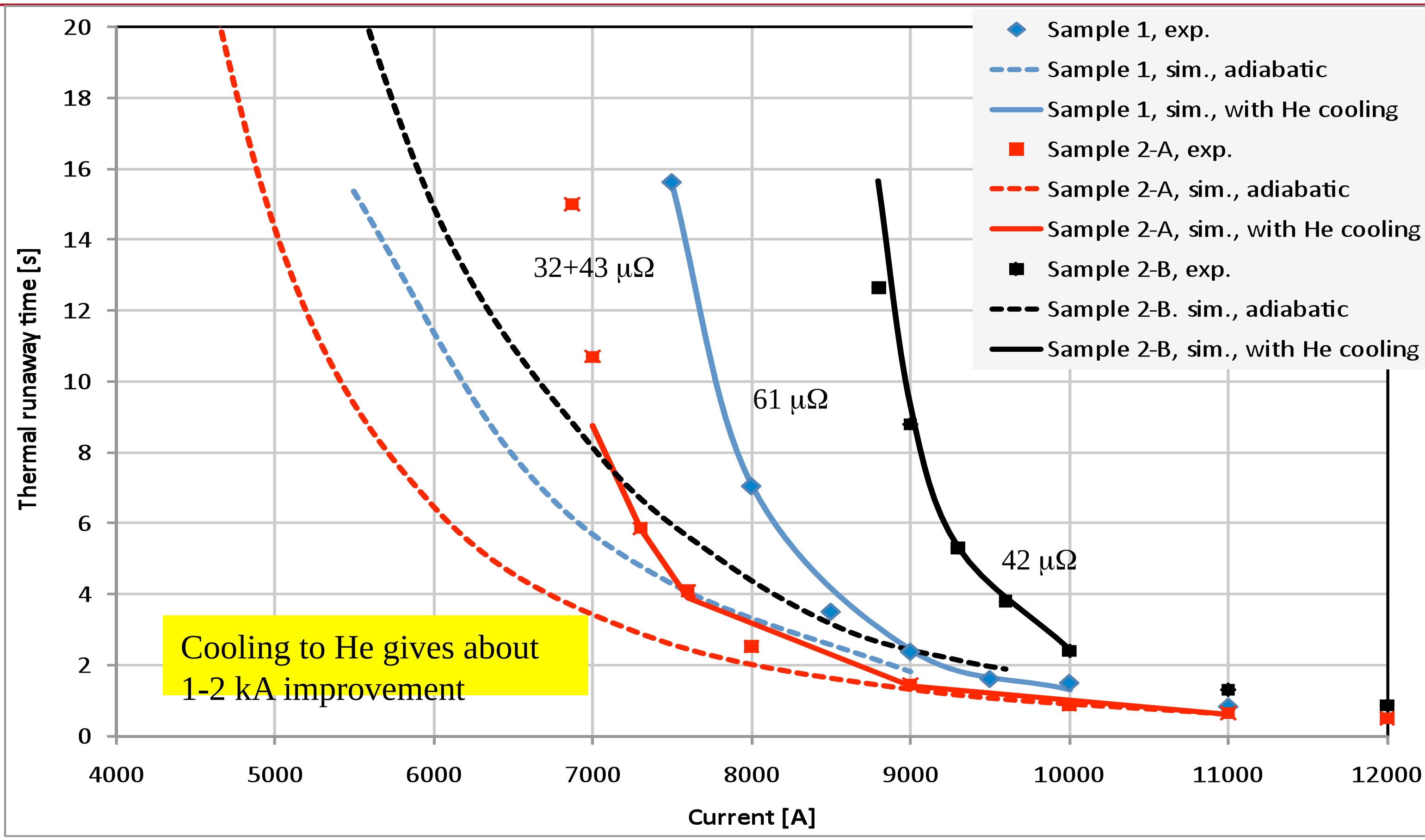
P. Limon

Thermal Runaway

Typical correlation experimental and calculated V(t) curves



Model Fit to FRESCA Data



Correlation experimental and calculated $t_{TR}(I)$ curves.

For each sample the effective heat transfer to the helium is individually fitted

	FRESCA Sample 1	FRESCA Sample 2A	FRESCA Sample 2B
Defect type	Calculated for a single-sided defect B		
RRR bus	Scaled to 160		
RRR cable	Scaled to 80		
Interconnect insulation	Calculated for machine type		
Effective cooled bus surface	Scaled to 90%		
Field	Self field		
Helium environment	LHe at 1.9 K		
Effective heat transfer factor (resulting from fit to experimental data)	1.8	1.6	0.89
I_{safe} for R_{addit}=67 $\mu\Omega$ with τ=10 s (RQ)	7.13 kA	7.03 kA	6.95 kA
I_{safe} for R_{addit}=26 $\mu\Omega$ with τ=20 s (RQ)	11.95 kA	11.48 kA	11.06 kA

P. Limon

Quench scenarios

Quenches in LHe:

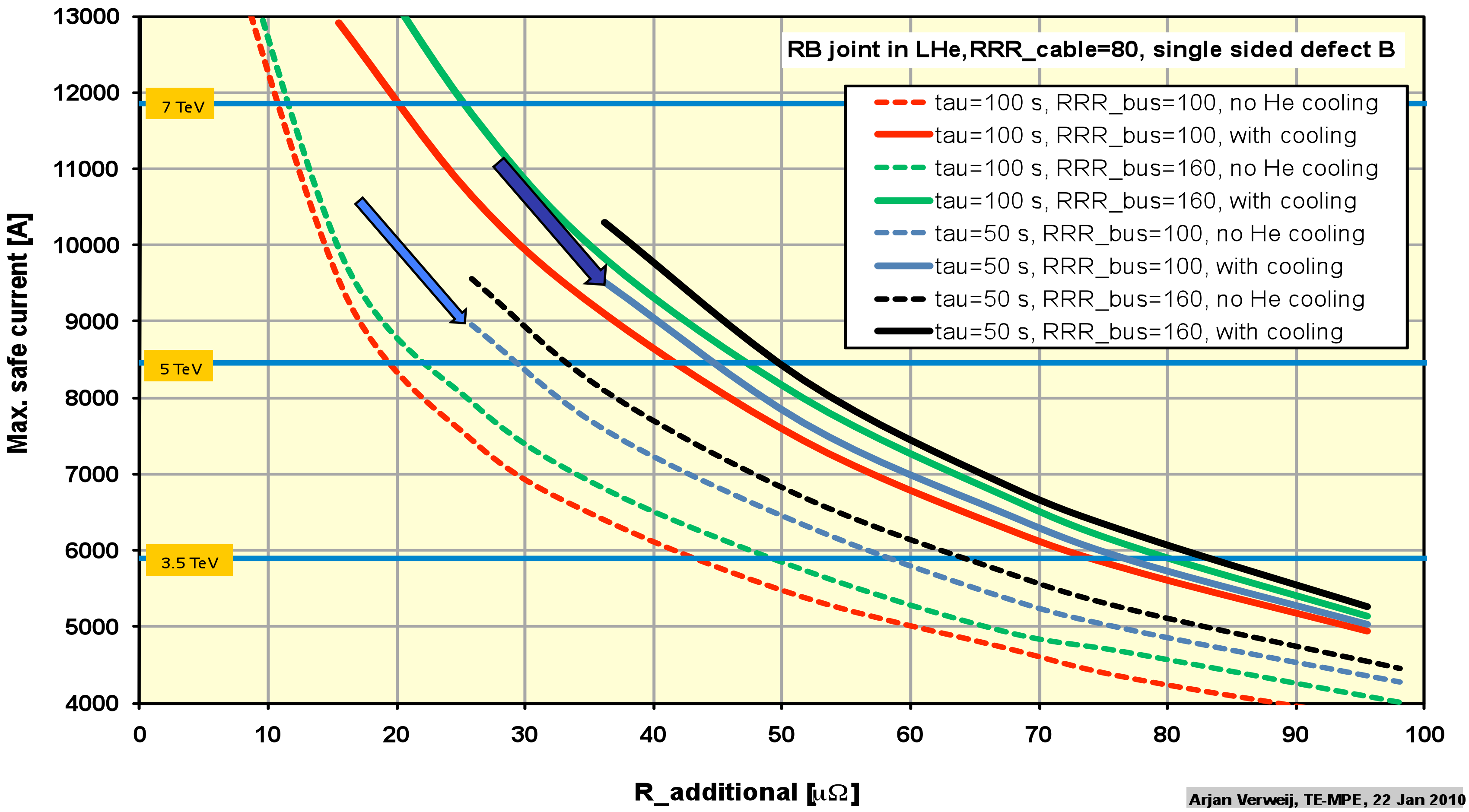
- Quench due to mechanical movement of the Non-Stabilized Bus Cable. Not very likely below 7 kA (because all sectors already powered up to 7 kA).
- Quench due to global beam losses.
- Quench due to normal zone propagation through the bus from an adjacent quenching magnet. Not possible below 6 kA (RQ) and 8 kA (RB) respectively.

Quenches in GHe:

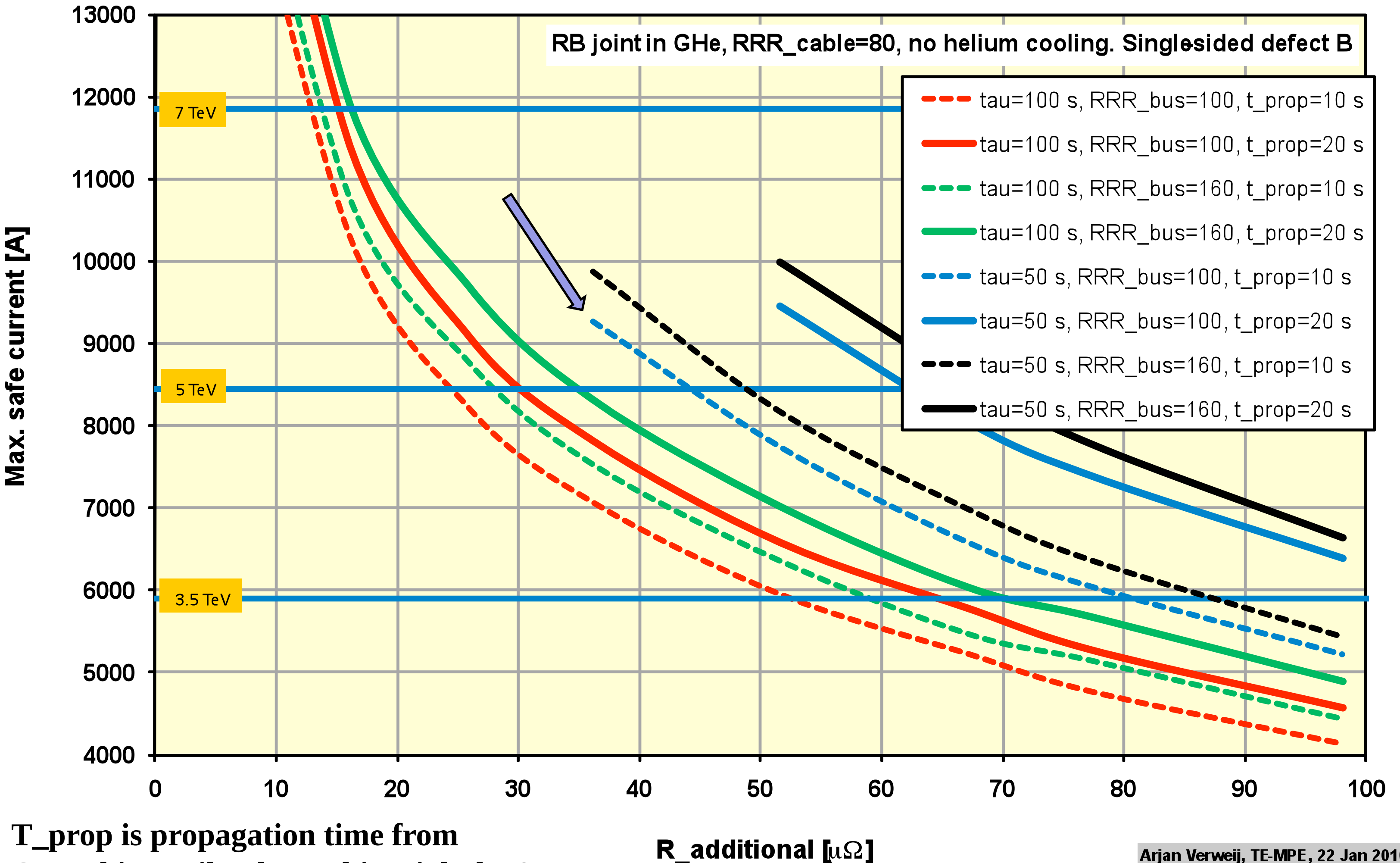
- Quench due to warm helium from adjacent quenching magnet. Very unlikely below about 5 kA, almost certain above 9 kA. Time between quench of magnet and quench of interconnect depends mainly on:
    - current,
    - number of magnets that are quenching,
    - position in the cryogenic cell.

For the calculations I will assume no cooling to helium and a propagation time of:
10 s for high current quenches (I>11 kA),
20 s for intermediate currents (7-9 kA).

RB in LHe


RB joint in LHe,RRR_cable=80, single sided defect B
tau=100 s, RRR_bus=100, no He cooling
tau=100 s, RRR_bus=100, with cooling
tau=100 s, RRR_bus=160, no He cooling
tau=100 s, RRR_bus=160, with cooling
tau=50 s, RRR_bus=100, no He cooling
tau=50 s, RRR_bus=100, with cooling
tau=50 s, RRR_bus=160, no He cooling
tau=50 s, RRR_bus=160, with cooling
7 TeV
5 TeV
3.5 TeV
Max. safe current [A]
R_additional [μΩ]
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
0
10
20
30
40
50
60
70
80
90
100
Arjan Verweij, TE-MPE, 22 Jan 2010

RB in GHe



T_prop is propagation time from Quenching coil to bus. This might be 0.

Safe Operating Energy

Energy	τ_{RB} [s]	Max. $R_{addit,RB}$ [μΩ]	τ_{RQ} [s]	Max. $R_{addit,RQ}$ [μΩ]
3.5 TeV	50	76	10	80
5 TeV	75	43	15	41
7 TeV	100	11	20	14

- 3.5 TeV operation is "just OK" wrt estimated worse splice of 90 μΩ:
  - Conservative assumptions for RRR, ⇨ ongoing tunnel measurements
  - *Some assumptions not so conservative (PJL)*
- 5 TeV operation requires repair (and previous localization !) of the highest resistance outlier splices
  - High current pulsing / thermal amplifier diagnostics?
- 7 TeV operation requires extensive consolidation of splices for safest long-term performance
  - Segment measurements at warm (or any other temperature) are not accurate enough to detect these small resistance values
  - R_{addit} may degrade during the lifetime of the LHC
  - Especially for small resistances, the measured R_{addit}(300 K) may not be representative for R_{addit}(10 K)
  - a shunt has to be added on all 13 kA joints, also on those with small R_{addit}. Joints with high R_{addit} or joints with large visual defects should be resoldered and shunted

A. Verweij

Safe Running @ 13 kA

- Safe 13 kA operation requires $R_{addit,RB}$<11 mW and $R_{addit,RQ}$<14 mW. Proper quench protection is usually based on an adiabatic approach which further decreases the maximum R_{addit} to 8 and 13 mW. One can be sure that there are many hundreds of defects with larger R_{addit} in the machine. Better know-how of the RRR_{bus} might increase the maximum R_{addit} a bit, but they will stay well below 20 mW.
- ‘Segment’ measurements at warm (or any other temperature) are not accurate enough to detect these small values.
- “High current pulsing” seems no option given the large number of defects, but might eventually be useful for a final in-situ qualification test of the circuits.
- R_{addit} may degrade during the lifetime of the LHC.
- Especially for small resistances, the measured R_{addit}(300 K) may not be representative for R_{addit}(10 K).

! Conclusion: For safe running around 7 TeV, a shunt has to be added on all 13 kA joints. Joints with high R_{addit} or joints with large visual defects should be resoldered and shunted.

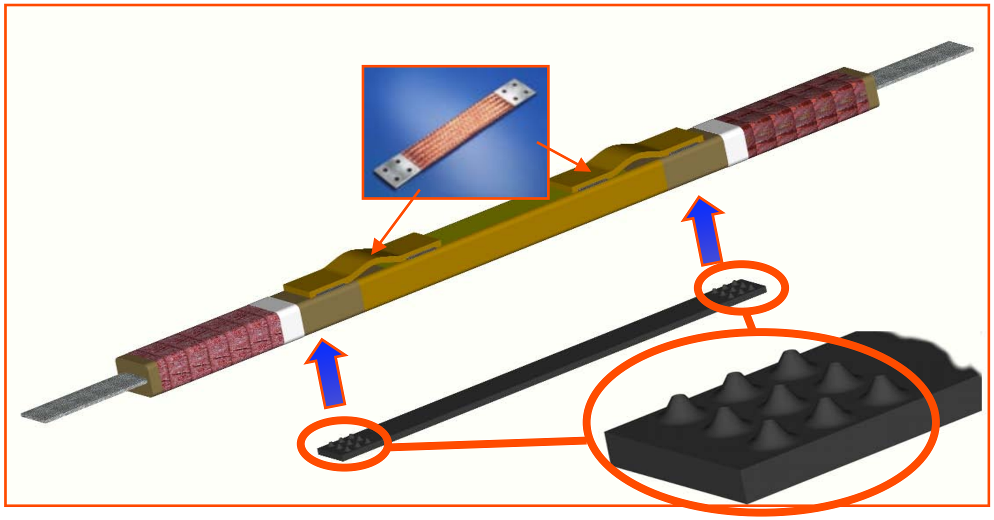
Personal Thoughts

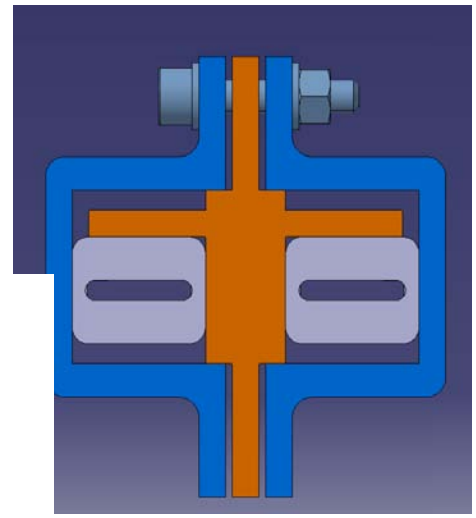
- **Is running at 3.5 TeV safe?**
  - I think it's marginal
    - LHC has used a non-adiabatic model to determine that $R_{addit} < 76\ \mu\Omega$ is safe.
    - An adiabatic model requires $R_{addit} < 56\ \mu\Omega$
    - It very likely that there are joints with $R_{addit} > 56\mu\Omega$
    - (In fact, it's likely that there are joints with that $R_{addit} > 76\ \mu\Omega$
  - Since $T_{max} \propto e^{\int I^2 dt}$ (at high T), a small reduction in current makes a big difference in temperature
  - **I think running at 3TeV x 3 TeV is wiser**

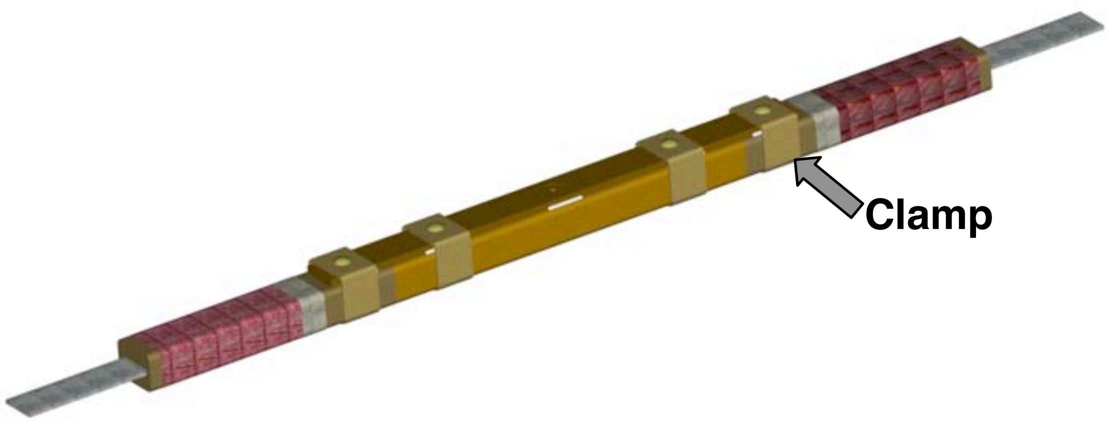
Personal Thoughts - 2

- **What about 5 TeV?**
  - All the "bad" joints have to be fixed
    - "Bad" = $R_{addit} > 25\ \mu\Omega$
    - It is known that there are many joints worse than that
    - There is no reliable way to locate them
  - Not likely to be able to find and repair joints to make 5 TeV running safe
- **7 TeV?**
  - Must fix/modify all the joints in the LHC
  - Will take a 12 month shutdown, at least
  - There is what appears to be a good concept for the repair

Present Joint Concept







Chamonix 2010

- **LHC Performance Workshop**
  - Other consequences, neutrinos, for example, were not discussed
    - – *Also there from Fermilab: H. Pfeffer, R. Flora, V. Shiltsev, E. Prebys*
- **Main items:**
  - Repair scenarios for LHC joints
    - Whether to have only one long shutdown or two shorter ones
    - Whether to try to fix things for 5 TeV
      - – *(The words "repair" and "fix" are not actually allowed at CERN, since they would imply that something was not done correctly, which is inconceivable.*
      - – *It's "consolidation.")*
  - Upgrades
    - Injectors
    - Inner triplets
  - Discussions of luminosity profile, safe energy and schedule
  - Other stuff (radiation, access procedures, etc., I will skip)

Joint Consolidation

- **Not feasible to do repairs that permitted 5 TeV running**
  - So, initial operation at 3.5 TeV, which was presented as "just safe"
  - The experiments strongly favored a long run at 3.5 TeV; at least 1 fb^{-1}
    - To surpass the Tevatron
    - It did not seem useful to try to upgrade the machine to 5 TeV during a short shutdown that would break up the run period
  - A run of 1 fb^{-1} or ~ 1 to 1.5 years, whichever came first
  - A long shutdown (>1 year) starting in late in 2011
    - No beam in 2012

Long Shutdown

- **Make the LHC capable of 7 TeV operation**
  - This involves opening every interface, installing the shunt and clamp and repairing obviously bad joints. 6 joints/interface
  - There are many other joints (DFBs, etc.) and splices that may need modifications
  - Install clamshells of Vetronite (a conducting composite) around the beam tubes in the interfaces.
    - To prevent an arc from penetrating the beam tube.
  - Install more rupture disks, some fast-acting valves, etc.
  - Vacuum relief ports on every dipole cryostat. (this is already ~ half done)
- **This is the minimum that should be done**
- **Will the LHC ever get to 7 TeV/beam**

Upgrades 1

- **Injector upgrades - PS2** (50 GeV) **& SPL** (Superconducting Proton Linac)
  - Two reasons for injector upgrades
    - More intensity for the LHC
    - The PS is 50 yrs old and will be hard to keep running
  - However:
    - Intensity limitations are set by various instabilities in the SPS, not the injectors
      - *This was known for many years. Why now?*
    - The only 50 yr old things in the PS are the magnet yokes, and they are being slowly consolidated. Everything else has been replaced at least once.
    - Since the upgrades would not be operational for at least 10 yrs, the PS and Booster would have to be made to run another 10 yrs. Why not make them ready to run another 20 yrs?
- **Hence: No new PS2 and no new SPL**
  - **"Saves" an estimated $1.5 billion**

Upgrades 1.5

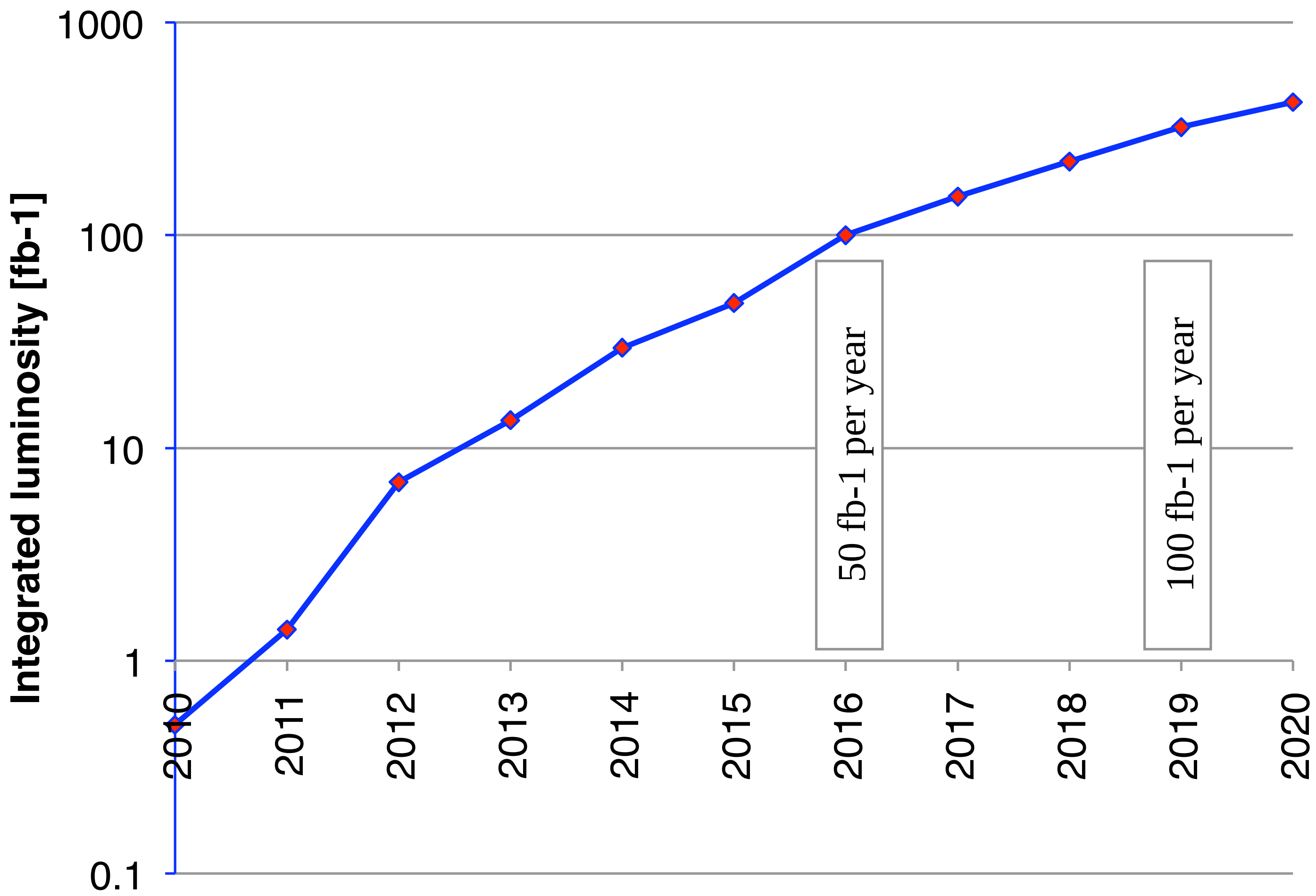
- **Hence: No new PS2 and no new SPL**
  - This had obviously been decided in advance and presented
    - There was some argument, mostly from Roland Garoby
  - Instead, there are other approaches
    - Work on the SPS limitations
    - Possibly increase the energy of the PSBooster
  - In the end, the LHC beam intensity is determined by machine protection, i.e. collimators
  - **All this will take some fraction (half?) of the $1.5 billion**

Upgrades 2

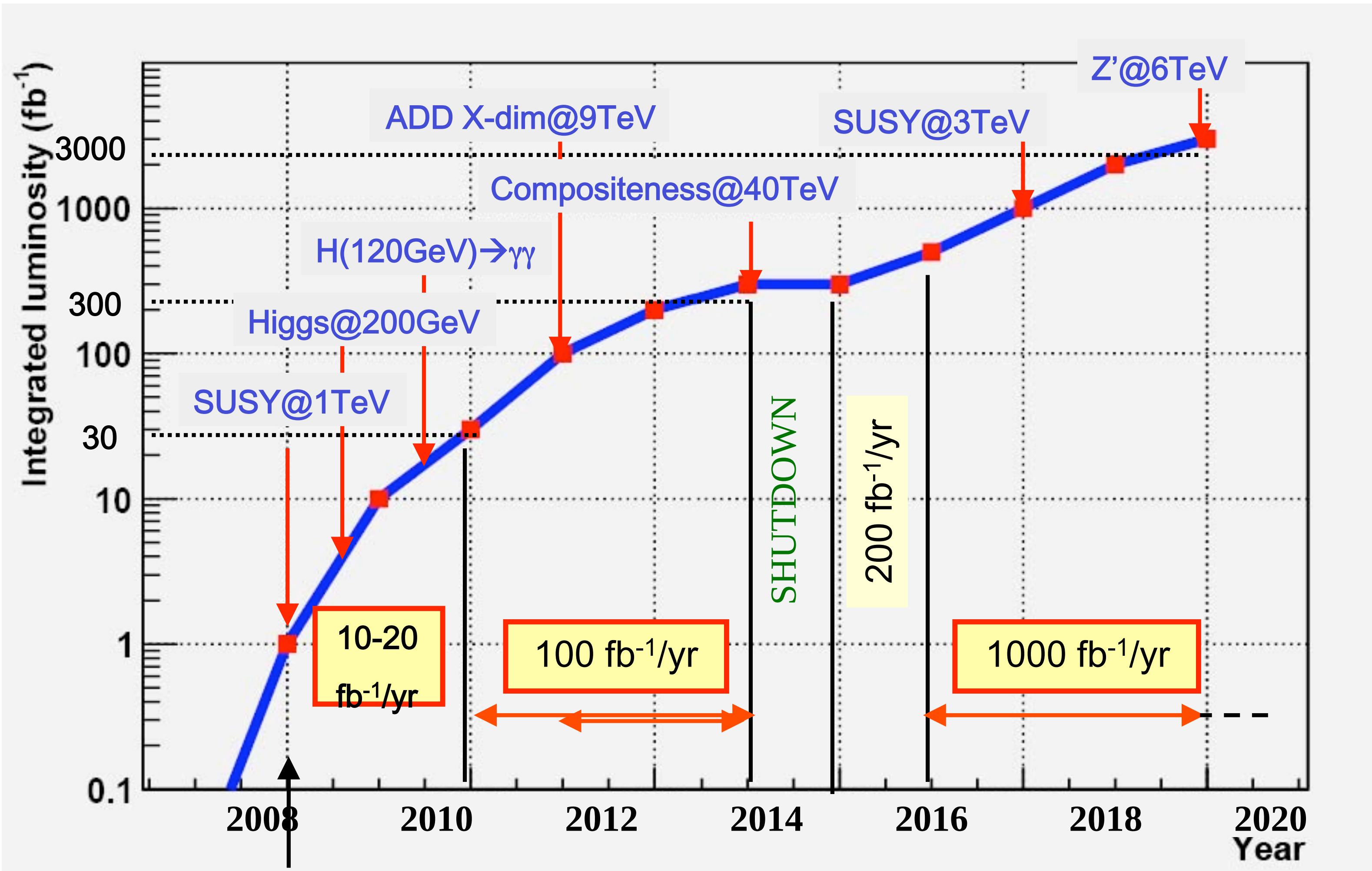
- **New inner triplets at IR1 (ATLAS) & IR5 (CMS)**
  - Three reasons for new inner triplets
    - Larger aperture allowing lower β^* and perhaps more intensity
      - *The inner triplets are the aperture limitation and determine the collimator settings*
    - At some point must be replaced due to radiation damage. Years ago, this was expected to be about 2015.
    - LHC wants to generate spare triplet quad spares by replacing the four sets before they are radiation damaged.
  - However:
    - Schedule is already delayed to 2015 installation, at earliest
    - It will take some years to get back the integrated luminosity lost during the shutdown
    - The inner triplets will not suffer radiation damage until much later than previously thought with the present expected luminosity profiles. Perhaps 2018 – 2020
    - The spares issue was not discussed.
  - The people working on the new inner triplets are the same people who are working on the joint consolidation.
    - This will make the inner triplets at least a year later, to 2016 at earliest
- **The inner triplet upgrade will be "discussed."** **There is no set schedule.**

Luminosity Estimates

Pushing to nominal in 2016 and taking a couple of years to get to get to ultimate (Thanks to M. Lamont)



In comparison with…



Conclusions from Steve Myers

- **The Luminosity Targets set by the detectors are:**
  - $3000 fb^{-1}$ (on tape) by the end of the life of the LHC
  - → 250-$300 fb^{-1}$ per year in the second decade of running the LHC
- **The Upgrades needed to attack these goals are**
  - o SPS performance improvements to remove the bottleneck
  - o Aggressive consolidation of the existing injector chain for availability reasons
  - o Performance improvement of the injector chain to allow phase 2 luminosities
  - o a newly defined sLHC which involves
    - luminosity levelling at ~5-6x $10^{34} cm^{-2} s^{-1}$ (crab cavities etc…)
    - At least one major upgrade of the high luminosity insertions

Personal Perspectives

- **The "reconsideration" of the injector & Phase 1 upgrades**
  - Maybe it's just the technical arguments, but…
  - Saves $1.5 billion.
    - Do they expect a decrease in the CERN budget after the loan is paid off?
    - If the budget stays up, perhaps they want to invest in CLIC R&D
      - *The next step in CLIC R&D is estimated at ~$700 million*
      - *The "wish list" of various machine improvements uses the rest*
  - What happens to the CERN neutrino program?
  - I think that Linac 4 might also be on the chopping block
  - DOE is unlikely to invest in APUL with no upgrade schedule
    - This "saves" $32 million spread over 4-5 years, roughly half to Fermilab
    - We need to find something for these $ that will keep it in the HEP budget
      - *BNL is also affected; perhaps more than Fermilab*
- **New schedule & luminosity projections**
  - Should we run the Tevatron longer?